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Effect of display resolution and antialiasing on the discrimination of simulated-aircraft orientation

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Effect of display resolution and antialiasing on the discrimination of simulated-aircraft orientation

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Abstract

In Experiment 1, antialiasing was found to improve performance on an orientation-discrimination task, whereas increasing display pixel-count did not. The latter finding was attributed to a decrease in image contrast associated with driving the CRT beyond its effective bandwidth. In Experiment 2, it was found that display resolution is the primary determinant of orientation-discrimination performance. This performance was not significantly improved by increasing antialiasing beyond a minimal level, suggesting that greater image detail can be substituted for antialias filtering. Finally, data obtained from an objective target-size calibration showed that nominal target size often does not accurately reflect the size (and hence distance) of simulated targets.

Keywords: Spatial resolution; Orientation-discrimination; Antialiasing; CRT displays

1. General introduction

The performance of visual tasks in a flight simulator can be affected by both display and image properties. One important display property is the pixel-count, also referred to as display addressability or the number of displayed pixels. Advances in display technology are often measured in terms of increased pixel-count, although it is generally recognized that display spatial resolution is a better indicator of the visual tasks that a display can support [1,2].

There have been several attempts to study the effects of display resolution on the performance of visual tasks. For example, Kennedy et al. [3] measured the simulated distance at which the orientation of aircraft targets, displayed using light-valve projectors, could be discriminated and they found that display resolution had a significant effect on discrimination. However, their technique for measuring resolution was subjective and incompletely described, and so their measurements cannot be directly compared to those reported in other studies. Warner et al. [4] measured detection thresholds for stripes placed on simulated cylindrical objects of various sizes, and they also found a significant effect of display resolution. Their technique for specifying resolution was also non-standard, however, and so again it is difficult to generalize their results. Finally, Ziefle [5] attempted to relate visual performance on a reading task to display resolution. However, the actual display characteristic varied in this case was the number of displayed pixels. It appears that resolution was effectively varied in Ziefle's first experiment, and, in addition, display appearance was assessed in her second experiment. However, there was again no direct measurement of spatial resolution that would allow the results to be compared to those of other studies. Many other studies concerned with both engineering and perceptual issues may be cited in this context [2,6–8]. Thus, although the importance of specifying display resolution is often recognized, it is not consistently measured, and there appears to be no generally accepted procedure for specifying it in the context of applied visual and perceptual research.

In addition to display properties such as spatial resolution, image properties also determine how well visual

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tasks can be performed using simulated imagery. One commonly used technique that can affect the properties of a displayed image is antialiasing. This technique effectively decreases the spatial detail of the target in order to improve its appearance in either the spatial or temporal domains, or both [9]. Increasing either display pixel-count or display resolution or implementing antialiasing can increase system costs, and it can also be computationally expensive. Therefore, in order to use a simulator most effectively, these features must be used judiciously and in accordance with the visual task being performed. This in turn requires that they be both accurately measured and assessed in simulator applications.

We report here the results of two experiments conducted to assess the effect of display pixel-count, display resolution, and antialiasing on the performance of a task requiring high spatial detail—namely, the discrimination of aircraft orientation in an air-to-air environment. In Experiment 1, target-orientation discrimination was measured for various display pixel-counts. In addition, two levels of antialiasing were tested. In Experiment 2, the effects of display spatial resolution on target-orientation discrimination were tested directly. As discussed above, previous studies have varied image and display properties related to spatial resolution, but have not assessed it directly using measures that are relevant to visual and perceptual research. In this study, a standardized and intuitive method of assessing display spatial resolution is used, and the resulting data are compared directly with performance in the discrimination of simulated-aircraft orientation.

2. Experiment 1

In this experiment, we determined the simulated distance at which aircraft orientation could be discriminated using a CRT display similar to those used in an operational, tactical-flight simulator [10]. The purpose of this experiment was two-fold: first, to obtain baseline data on the relationship between pixel-count and target discrimination, and second, to determine how target discrimination is affected by the spatial and temporal variations introduced by antialiasing. The second question has both theoretical and practical implications because, whereas target discrimination is dependent on the display of high spatial detail, high-frequency components unrelated to the image can be introduced by aliasing. Thus, target detail can not only be reduced by spatial and temporal artifacts, but it can also be reduced by the image processing techniques (such as antialiasing) used to remove them. Finally, a technique is described for measuring the size of displayed targets in order to assess the accuracy with which target distance is simulated.

2.1. Methods

2.1.1. Observers

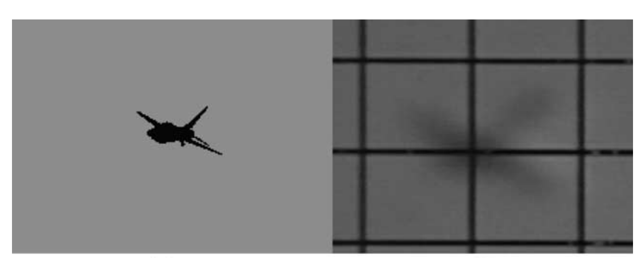
Seven non-pilots served as observers. Each had normal or corrected to normal vision as determined by the acuity, binocular vision, color vision, and phoria tests of the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

2.1.2. Stimuli and apparatus

Fig. 1a shows one of the two F-16 models used in the present study. The model shown has a bank of 30° and a heading of −15°. The other model had a +15° heading. Fig. 1b shows a digitized video image indicating approximately how the model appeared as displayed at a simulated distance of 3281 ft, except that it has been magnified by about 3.4×. The grid shown was used for target-size calibration only and was not present during the collection of the target-discrimination data. The aircraft targets were simulated by a MetaVR (Brookline, MA) PC-based image generator (IG) equipped with a NVIDIA (Santa Clara, CA) GeForce3 video card.

Imagery was displayed at either 1280×1024 or 2048×1536 pixels (referred to here as pixel-counts of 1280 and 2048, respectively). Aircraft targets were simulated at distances ranging from 3281 to 10,663 ft and were rear-projected onto the front channel of a Mobile Modular Display for Advanced Research and Training (M2DART) [10]. The background image on the front channel, as well as the other three forward channels, was a simulated, light-blue sky whose luminance was approximately 4 fL. All images were displayed using Barco Model 808 CRTs (Barco, Inc., Kennesaw, GA), and a 1.2 gain rear-projection screen (Proscreen, Inc., Medford, OR). Observers were seated 36 in. from the display, and indicated their responses using a mouse.

The targets were moved in a small circle (0.06° radius) such that one revolution was completed during each 3-s trial, while the heading direction relative to the observer was kept constant. This was done so that the target would move across several pixels during the course of the trial, thus



(a) (b)

Fig. 1. (a) An aircraft model (30° bank, −15° heading) that was used as one of the targets in the present study. (b) A photograph of the model as simulated at a distance of 3281 ft, except that it has been magnified by 3.4×, for illustrative purposes. The grid shown was present only during the size-calibration portion of the present study.

averaging out any mismatches between the image pixels and the display pixels.

Display spatial resolution was estimated using procedures similar to those suggested by VESA [11,12]. Briefly, vertical and horizontal black-and-white grille patterns were generated by the IG and projected by the display to be measured. A CCD camera was then used to measure the luminance of the grille patterns as the width of the grille lines was varied. A contrast value was calculated from the luminance measurement, and the grille-line width corresponding to a contrast of 25% (recommended by VESA) was estimated. Finally, the measured display resolution was determined by dividing the nominal pixel-count by the extrapolated grille-line width corresponding to the criterion contrast level (as an example, for a 1280×1024 display, if a vertical grille-line width of 1.8 pixels were required to achieve a 25% contrast between the light and dark lines, the measured horizontal resolution would be 1280/1.8=711 lines].

2.1.2.1. Antialiasing. Unfiltered imagery as well as imagery filtered at two levels of antialiasing (2× and 4×) were studied. The procedure used by the video card to implement 2× antialiasing is illustrated in Fig. 2. This illustation is based on a description provided by the graphics card manufacturer [13]. The squares represent the displayed pixels, and the white dots represent the sample points that determine whether and with what luminance the pixel is displayed. In the case of no antialiasing and a black target on a white background, a pixel is displayed as black (lowest luminance) if the target intersects the associated sampling point, and it is displayed as white (highest luminance) if it does not (see upper-right panel). In the case of 2× antialiasing, there are two sampling points associated with each pixel, and the pixel is displayed as black only if the target intersects both of them (see bottom panels in Fig. 2). If a portion of the target intersects only one sampling point, that portion is displayed as gray (i.e. an average of the black and white levels). The situation is analogous for 4× antialiasing except in that case there are four sampling points associated with each displayed pixel, and hence there would be five possible luminance levels for each pixel.

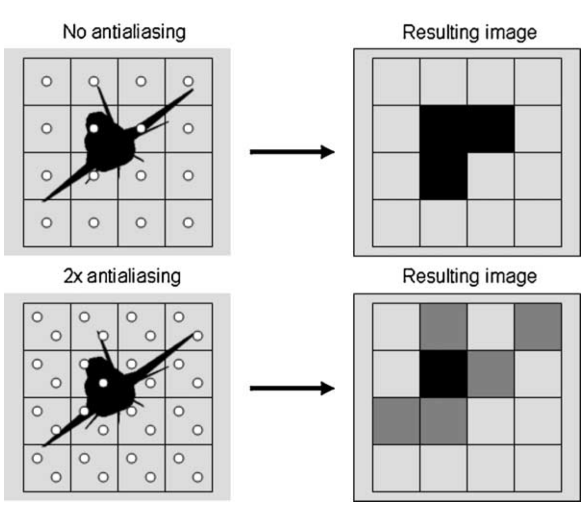


Fig. 2. An illustration of the antialiasing algorithm implemented by the video card used in the present study.

2.1.2.2. Target-size calibration. Due to mismatches between the simulated-target and the array of display pixels by which it is displayed, small targets will change size and shape as they are moved within the visual scene, even at a constant simulated distance. Therefore, the targets were moved in a circular pattern during each trial in order to minimize the visual effect of these changes. In order to assess the accuracy of the nominal simulated distance determined by the IG, it was necessary to quantify the variations in target size, and relate them to the orientation-discrimination data. To this end, the size of the target aircraft was measured by videotaping target presentations at each of the simulated distances. During videotaping, a transparency with a grid consisting of 5 mm squares was placed over the target aircraft position on the rear-projection screen. The size of the target aircraft was then measured every 10 frames on the videotape for each simulated distance, pixel-count, and antialiasing condition. Approximately 90 size measurements were obtained for each simulated distance. This procedure was repeated for each pixel-count and each level of antialiasing.

2.1.3. Procedure

The first trial in each session was initiated by the observer. In each trial, the observers viewed the F-16 stimulus and responded as to whether the aircraft appeared to be pointed to the left (shown in Fig. 1a) or to the right. The stimuli were presented near the center of the display, and each trial lasted for 3 s or until the observer responded. The total number of trials per observer was 960 (6 distances × 2 pixel-counts × 2 antialiasing levels × 2 orientations × 20 repetitions). The response data for the two orientations were combined. A threshold discrimination distance was obtained by fitting a Weibull function [14] to the proportion correct versus distance data, and finding the distance corresponding to a criterion proportion—correct of 0.816.

2.2. Results

As shown in Table 1, the number of resolved vertical lines (i.e. the horizontal resolution) was 704 for the 1280 pixel-count condition and 741 for the 2048 pixel-count condition. These values changed to 694 and 718 resolved lines, respectively, when 2× antialiasing was used. Thus, the use of 2× antialiasing did not significantly affect measured display resolution.

Table 1
Measured number of resolved lines and target orientation-discrimination distance for each of the conditions of Experiments 1 and 2

Pixel count (horizontal)	Resolved lines	Discrimination threshold (nominal-ft)	Discrimination threshold (mean size-ft)
Experiment 1 (no antialising)			
1280	704	6691	7210
2048	741	6785	8000
Experiment 1 (2 × antialising)			
1280	694	7328	8000
2048	718	7048	7736
Resolution level	Resolved lines	Discrimination threshold (nominal-ft)	Discrimination threshold (mean size-ft)
Experiment 2 (2 × antialising)			
Low	544	5431	6910
High	1047	7019	9619
Experiment 2 (4 × antialising)			
Low	560	5484	7226
High	1075	6898	8813

2.2.1. Target-size calibration

Fig. 3 shows the distributions of target sizes obtained by the videotape calibration procedure for each of the simulated distances tested under the no-antialiasing condition. The solid line associated with each target-size distribution indicates the nominal size based on the visual angle appropriate for the simulated distance and for the size of the F-16 model. The visual angle of the F-16 target was calculated from its foreshortened, displayed width of 31.7 ft. The dashed lines indicate the actual target size as

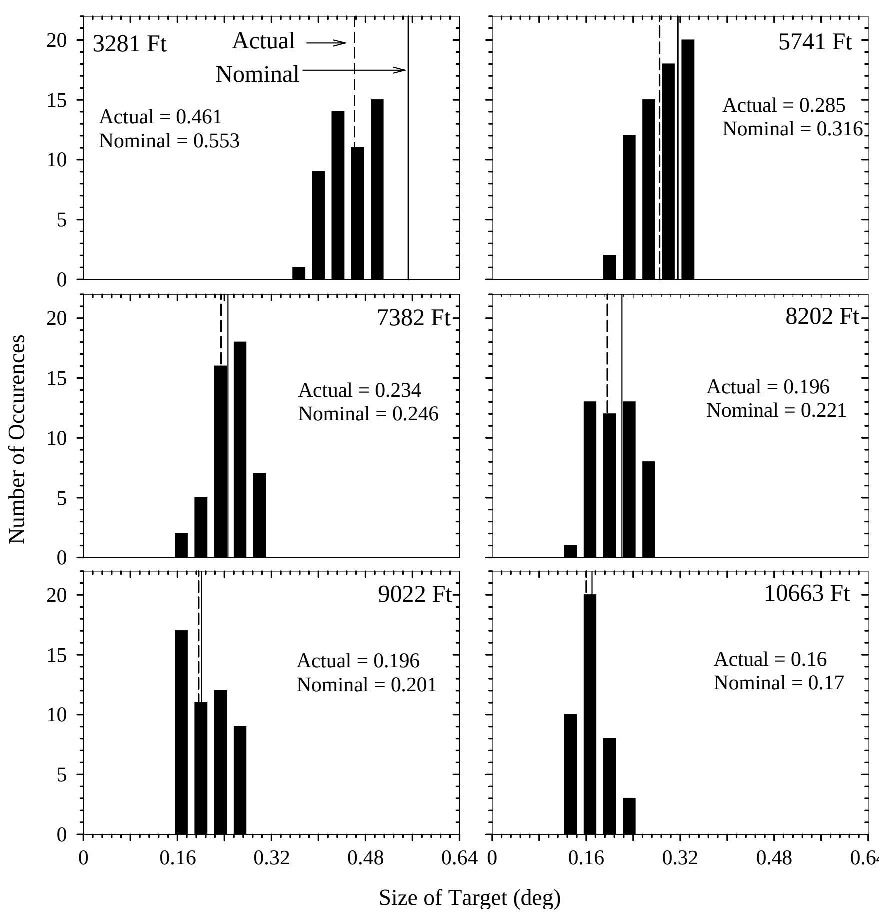


Fig. 3. Target-size distributions obtained at various simulated target distances for the 1280 pixel-count/no-antialiasing condition of Experiment 1. The mean of each distribution, referred to here as actual size, is indicated by the dashed vertical line, and the associated nominal simulated size is indicated by the solid vertical line.

defined by the mean of the target-size distributions. The actual target size is in all cases smaller than the nominal size. Although the *absolute* difference between the actual and nominal target sizes is greatest for the larger targets (i.e. 3281 and 5741 ft), the *percentage* difference varies between about 2 and 17%, and averages about 10%. The aspects of the data in Fig. 3 just described were similar for the 2×-antialiasing condition. The percentage difference between actual and nominal target size also averages about 10%. However, the range of differences is somewhat smaller—approximately 9–14%.

2.2.2. Target-discrimination data

Typical data that illustrate how the threshold orientation-discrimination distances were estimated are shown in Fig. 4. The data are the mean proportion of correct discriminations for one observer as nominal target distance was increased under both the no-antialiasing and 2×-antialiasing conditions. Weibull functions were first fitted to the data, and they are shown by the solid lines placed through the data points. Next, a criterion level of the proportion of correct responses was chosen in order to estimate threshold discrimination distance. The chosen criterion level of 0.816 is indicated by the horizontal dashed line. Finally, the threshold distance for orientation-discrimination was determined by finding the simulated distance corresponding to the threshold level, indicated by the vertical lines.

The mean orientation-discrimination distances for all four combinations of pixel-count and antialiasing level are shown in Fig. 5. The bar graphs indicate the means of the distances obtained from all observers by the procedures illustrated in Fig. 4. The black bars represent data obtained using the nominal target sizes, and the white bars represent data obtained using the actual target sizes determined from the videotape calibration procedure.

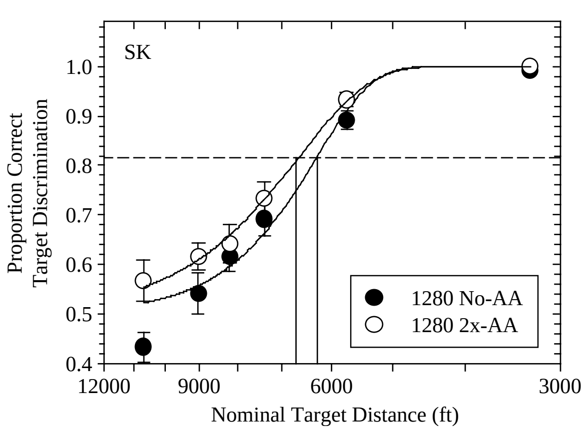


Fig. 4. The proportion of correct orientation-discriminations plotted as a function of the simulated distance of the target for two experimental conditions of Experiment 1. The horizontal dashed line shows the threshold proportion-correct, and the vertical solid lines show the derived threshold target distances. Analogous data for all observers were averaged to obtain the data for each of the four experimental conditions shown in Fig. 5.

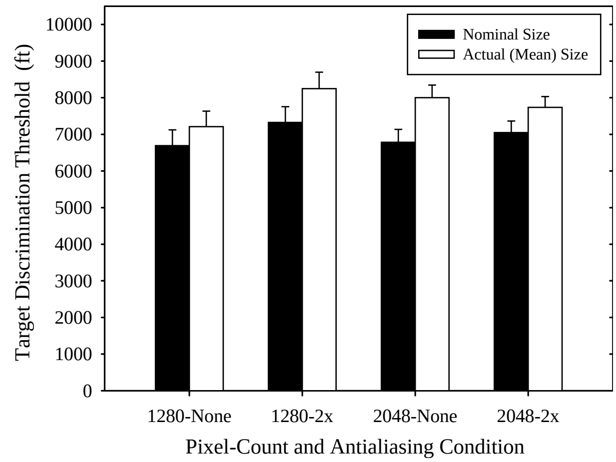


Fig. 5. Orientation-discrimination thresholds for each of the conditions tested in Experiment 1. The white and filled bars represent thresholds calculated using actual and nominal target sizes, respectively. The data are the mean for all eight observers, and the error bars are the standard errors of the mean about each data point.

Averaged over the other factors (antialiasing and size/distance measure), the threshold target-discrimination distances shown in Fig. 5 were 7369 and 7392 ft for the 1280 and 2048 pixels-counts, respectively. A within-subjects repeated measures ANOVA indicated that this difference was not statistically significant [$F(1,6)<0.02$, $p>0.8$]. The analogous distances for the no-antialiasing and 2× antialiasing conditions were 7171 and 7590 ft, respectively. This difference was statistically significant [$F(1,6)>17$, $p<0.01$]. Finally, the mean threshold target discrimination distances for the nominal and actual target size metrics were 6963 and 7799 ft, respectively. This difference was also statistically significant [$F(1,6)>1600$, $p<0.01$]. There were also several significant interactions: Pixel-count × antialiasing ($F(1,6)>21$, $p<0.01$), pixel-count × size/distance measure ($F(1,6)>19$, $p<0.01$), and pixel-count × antialiasing × size/distance measure ($F(1,6)>285$, $p<0.01$). Antialiasing had a greater effect on thresholds for the 1280 pixel-count condition compared to the 2048 pixel-count condition.

2.3. Discussion

The data of Fig. 5 show that increasing the number of pixels in the displayed image by a factor of 2.4 (i.e. from about 1.3 to 3.1 million) had no significant effect on the distance at which aircraft orientation could be identified. The fact that increasing the number of pixels (and thus decreasing the size of each pixel) did not improve target-orientation discrimination seems counterintuitive. These results can be accounted for by considering the spatial resolution measurements. Despite the fact that the horizontal pixel-count increased by 60% between the 1280 and 2048 pixel-count conditions, the spatial resolution, or the number of resolved pixels did not change. The horizontal spatial resolution for each condition was about 700 lines. These data demonstrate the importance of specifying display resolution when evaluating visual or perceptual performance on simulator systems. As was discussed earlier, and will be discussed further in Section 5, several previous attempts to relate visual performance to display resolution in a flight-simulator environment did not fully specify spatial resolution.

The data of Fig. 5 also show that 2×-antialiasing improved target-orientation discrimination, even though it did not improve the spatial resolution of the displayed image (see Table 1). A comparison of the upper and lower panels in the figure shows that twice as many samples are used in the process of rendering the final image with 2×-antialiasing as compared to no antialiasing. Thus, 2×-antialiasing will increase the likelihood that small features of the aircraft model (such as the wingtips of a distant aircraft) will be visible in the rendered image. The use of antialiasing may have kept the target visible for a greater percentage of the experimental trial and hence improved discrimination performance. The same mechanism would be expected to reduce flickering of the target since this is caused by changes in luminance associated with movement of the target across adjacent display pixels. With no antialiasing, the luminance of rendered pixels would change greatly (i.e. from the target luminance to the background luminance) even when the target is moved a small amount. These relatively extreme changes in pixel luminance would also be expected to increase the amount of flicker in the rendered aircraft target.

There is also evidence in the size calibration data of the flickering of the displayed target. As shown by the data of Fig. 3, the measured mean target size for the 3281-ft condition is 17% smaller than the size nominal for an F-16 aircraft simulated at that distance. This is because high-detail portions of the aircraft, such as the wings and tail, were not consistently displayed as the target was rendered during its movement across the fixed array of display pixels. This caused the target to appear to flicker. Antialiasing reduces this flickering because the image is represented in video memory by a larger number of samples. This increases the likelihood that the finer details in the aircraft target will be rendered in the displayed image. Increasing the pixel-count to 2048 also results in a greater number of samples, which may account for the reduced effect of the antialiasing for this pixel-count.

3. Experiment 2

The results of Experiment 1 indicated that pixel-count had no effect on the discrimination of target orientation, and that 2×-antialiasing improved performance by a small but significant amount. Although pixel-count may be related to spatial resolution, they are not equivalent measures. In order to investigate whether spatial-resolution, as assessed here, was a better predictor of visual performance, Experiment 2 was designed to measure target-orientation discrimination while varying spatial resolution and keeping pixel-count constant. The effect of an additional level of antialiasing was also tested in order to determine if the improvement found with the use of 2× antialiasing would be increased with 4× antialiasing.

3.1. Methods

3.1.1. Observers

Eight non-pilots served as observers. Each had normal or corrected to normal vision as determined by the acuity, binocular vision, color vision, and phoria tests of the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

3.1.2. Stimuli and apparatus

The target stimuli and target presentation procedures were identical to those used in Experiment 1. The targets were simulated at distances ranging from 3162 to 12,589 ft and again appeared at one of two headings (±15°) relative to the observer. The targets were simulated using a PC-based image generator (MetaVR, Inc., Brookline, MA) equipped with a NVIDIA (Santa Clara, CA) GeForce4 video card, and they were displayed using either a Barco Model 808 (Barco, Inc., Kennesaw, GA) or a VDC Marquis 8500 (VDC Display Systems, Cape Canaveral, FL) CRT projector. The simulated image once again subtended 72°×62° (52 in.×43 in.) at a viewing distance of 36 in., and it consisted of 1600×1200 pixels. Two levels of antialiasing (2× and 4×) were used (see Fig. 2 and Section 2.1.2.1).

The VDC projector was used to display the high-resolution targets, and the Barco projector was defocused and used to display the low-resolution targets. The spatial resolution of each projector was estimated by the same technique used in Experiment 1, and was found to be between 544 and 560 lines and between 1047 and 1075 lines for the low-resolution and high-resolution projectors, respectively.

3.1.3. Procedure

The testing procedures were identical to those of Experiment 1. Each session consisted of 240 trials (6 distances×2 headings×20 repetitions). The response data for the two headings were combined, and a threshold discrimination distance was obtained using the same procedure as described for Experiment 1.

3.2. Results

Fig. 6 shows the distributions of target sizes for each simulated target distance for the high-resolution/2× antialiasing condition. Once again, the solid line associated with each target-size distribution indicates the nominal size, based on the visual angle appropriate for the simulated

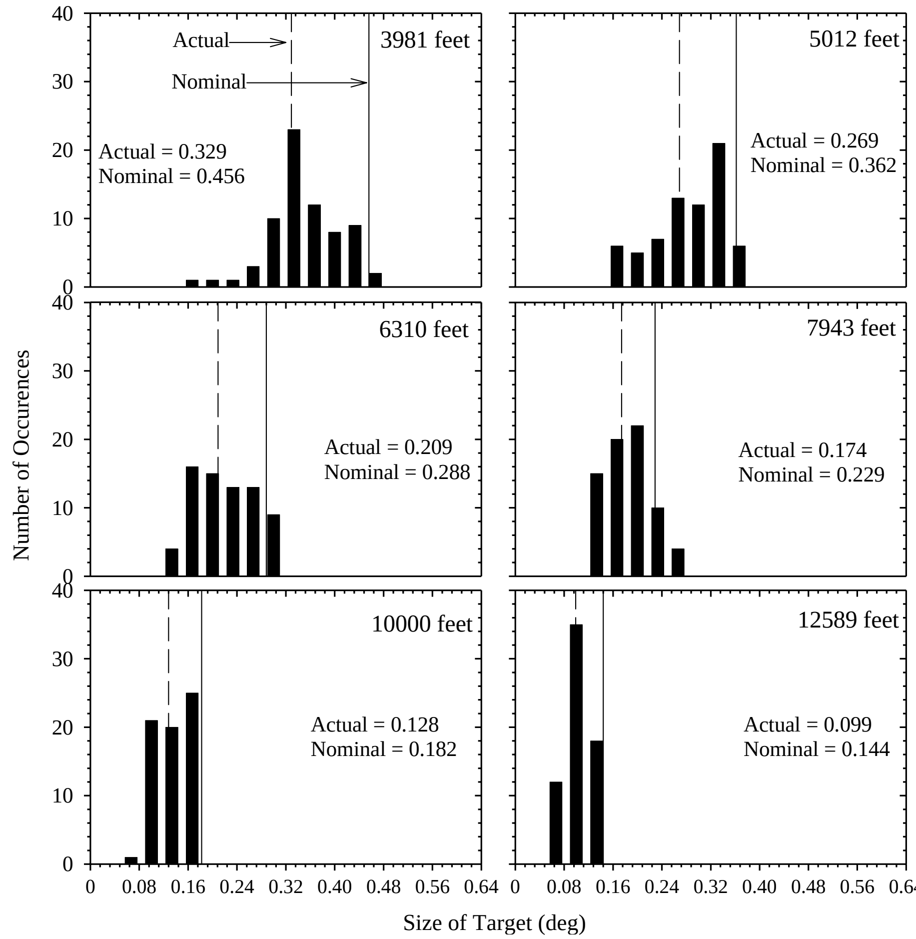


Fig. 6. Target-size distributions obtained from the videotaped calibration procedure as applied to the high-resolution/2×-antialiasing condition of Experiment 2. The mean of each distribution, referred to here as actual size, is indicated by the dashed vertical line, and the associated nominal simulated size is indicated by the solid vertical line.

distance and for the size of the F-16 model, and the dashed lines indicate the actual target size as defined by the mean of the measured target-size distributions. As was the case in Experiment 1, the nominal target size is greater than the actual target size, although this difference was larger in Experiment 2. For five of the six simulated distances tested, the measured distribution of sizes does not include with the nominal size. As was also the case in Experiment 1, the absolute difference between nominal and actual size is greatest for the larger targets (i.e. 3281 and 5741 ft), but the percentage difference is much less—it varies between about 24–31%, and averages about 28%. The aspects of the data of Fig. 6 just described were similar for the high-resolution/4×-antialiasing condition, and the low-resolution 2× and 4× conditions.

Fig. 7 shows the mean proportion of correct target discriminations as nominal target distance was varied for one observer in Experiment 2. These data were obtained using two levels of display spatial-resolution and two levels of antialiasing. A least-squares fit of a Weibull function was again used to estimate a threshold distance for each set of

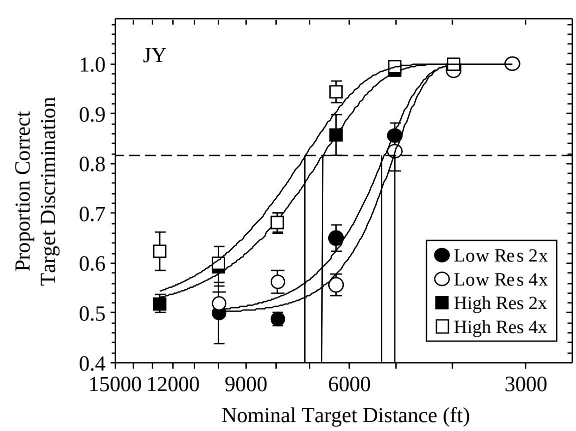


Fig. 7. The proportion of correct orientation discriminations plotted as a function of the simulated distance of the target for the four experimental conditions indicated. The horizontal dashed line shows the threshold proportion-correct, and the vertical solid lines show the derived threshold target distances. Analogous data for all observers were averaged to obtain the data for each of the four experimental conditions shown in Fig. 8.

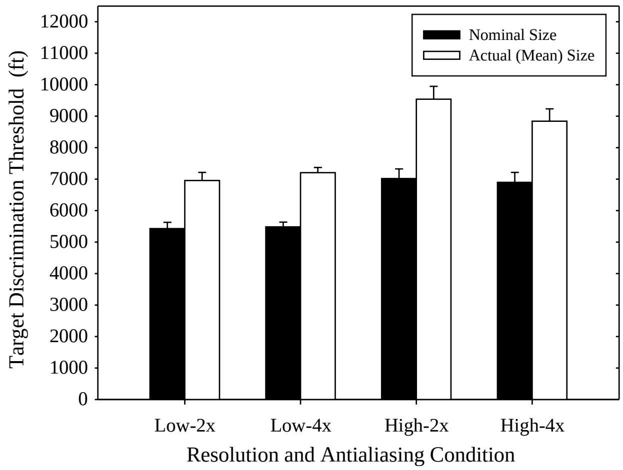


Fig. 8. Orientation-discrimination thresholds for each of the conditions tested in Experiment 2. The white and filled bars represent thresholds calculated using actual and nominal target sizes, respectively. The data are the mean for all eight observers, and the error bars are the standard errors of the mean about each data point.

data. The threshold level is indicated in Fig. 7 by the horizontal dashed line, and the corresponding threshold orientation-discrimination distances are indicated by the vertical solid lines. This procedure was repeated for each observer and the means of the resulting data are shown in Fig. 8 for target-distance thresholds based on both nominal (black bars) and actual (white bars) target size. A repeated measures analysis of variance indicated a significant effect of spatial resolution ($F(1,7)>61$, $p<0.01$), but no effect of antialiasing ($F(1,7)<2$, $p>0.5$). The effect of the size/distance measure was also significant ($F(1,7)>1000$, $p<0.01$). Thresholds were significantly greater when actual size was used in place of nominal target size. The following interactions, resolution × size/distance, antialiasing × size/distance, and resolution × antialiasing × size/distance were all significant ($F(1,6)>20$, $p<0.01$).

4. Discussion

It is not surprising that display spatial resolution would affect the performance of a task, such as target-orientation discrimination that requires the discrimination of high spatial detail. The value of the results of Experiment 2 is that they may be used to quantitatively relate task performance to display resolution because they were obtained using displays whose resolution was objectively measured.

As was the case in Experiment 1, increasing the level of antialiasing did not significantly alter the measured display resolution (see Table 1). This result suggests that a minimal level of antialiasing may be sufficient to improve performance on tasks of the kind studied here. Using a lower level of antialiasing may make available processing resources that can be used to improve other aspects of the simulation, such as scene content or frame rate.

5. General discussion

5.1. Specification of display resolution

The importance of specifying display resolution appears to be generally accepted, although it is often either not done, or done incompletely. We will discuss here several studies that demonstrate some of the many problems associated with performing spatial resolution measurements using non-standardized techniques. While we are critical of the studies cited, it should be noted that they all recognized the need for specifying resolution. Further, the resolution measurements made in those studies appear to be adequate to support the conclusions drawn.

Kennedy et al. [3] attempted to measure aircraft-aspect recognition for various levels of display resolution. They defined resolution as the visual angle of one just-resolvable TV line pair. Although not stated, 'just-resolvable' apparently refers to visual judgments made by one or more of the experimenters, but neither the observers nor the methods used to obtain these judgments were described. In addition, line width was apparently varied by changing the viewing distance to the display, which may introduce additional complications in the context of a visual discrimination task. The subjective approach used by Kennedy et al. to define resolution is generally accepted, and it can be used to specify the relative levels of resolution used in a given study. However, the results obtained using this technique are generalizable only if standardized experimental methods are used to perform the visual estimation of resolution. Although there are standardized test patterns, such as the SMPTE or radial patterns [15], for making these estimates, we know of no standardized techniques for visually estimating spatial resolution.

Another problem that may arise in the specification of display resolution can be seen in the study of Warner et al. [4]. These authors chose to use the half-maximum width of the line-spread function of their display as a measure of resolution. In defense of this choice, the authors cite Murch and Virgin [16] who contend that a narrower line-spread function is equivalent to higher resolution. This is true, however, only if the peak luminance of the functions compared is constant. The problem with this approach is illustrated in Fig. 9. Fig. 9(a) shows two hypothetical line-spread functions illustrated here by Gaussians with different peak luminances and different variances (i.e. widths). The Fourier transforms of these functions are also Gaussians whose widths (specifically, bandwidths) are inversely related to the widths of their corresponding line-spread function. These Fourier transforms are shown in Fig. 9(b), where it can be seen that whereas the narrower line-spread function (filled circles) results in a larger bandwidth, its lesser contrast results in the association of a lower spatial frequency (or, analogously, grille-line width) with a specified criterion-contrast level (see horizontal and vertical lines in Fig. 9(b)). Clearly, more than the width of

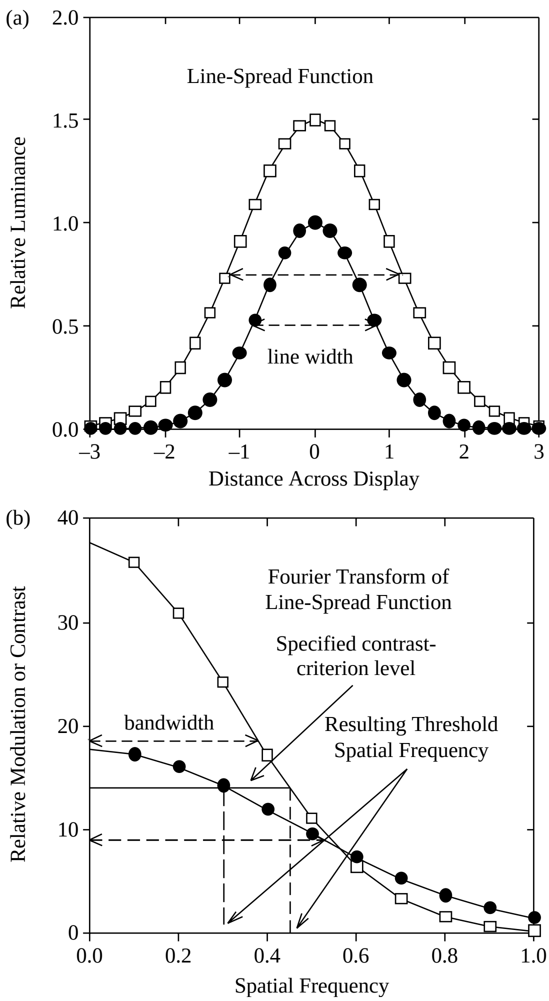


Fig. 9. Hypothetical Gaussian line-spread functions (a), and their Fourier transforms (b), illustrating the difference between bandwidth (dashed lines in b), and the spatial frequencies associated with a specified criterion-contrast level (co-linear solid line segments in b). In the context of the spatial-resolution measurement technique used here, spatial frequency is analogous to grille-line width.

a line-spread function must be considered when specifying spatial resolution. It is not clear why Warner et al. did not complete their analysis by Fourier transforming their line-spread functions to obtain an MTF, but even if they had, they would still have had to contend with the inherent difficulties associated with interpreting MTFs in the context of visual research (see Section 5.2 below).

As a final example, Ziefle [7] attempted to relate visual performance on a reading task to display resolution. Although pixel density was improperly used as a measure of display resolution, the relative luminance of the text characters and background that made up the experimental stimuli was measured. The problem here is that the calculated luminance ratios appear unrelated to pixel density. In fact, increasing pixel density resulted in a small increase in relative contrast. Ziefle also attempted to verify that varying pixel-counts resulted in perceivable differences in the test stimuli used. However, as was the case with Kennedy et al. [3], the perceptual data were obtained using ad hoc techniques that would be difficult to replicate. In addition, the perceptual data were not used in assessing the various performance measures that were the purpose of the study. Again, we suggest that this latter fact was due to the inherent difficulty in relating a subjective measure of resolution to visual performance data.

5.2. MTFs and visual research

A general problem associated with specifying spatial resolution by the MTF and related approaches is that doing so is inherently technical. The engineering and optical approaches to specifying resolution often involve transforming a spatial variable (typically a line-spread function) into the spatial frequency domain (typically a modulation transfer function [MTF]). There are many techniques for doing this, and although the results of those techniques are comparable, they are not always quantitatively identical and thus may be difficult to interpret and compare. Likewise, there is no intuitive way to conceptualize the relevant characteristics of the MTF (e.g. bandwidth) in order to relate it to visual or perceptual data. This problem is evident in the study performed by Näsänen et al. [17], for instance. These authors measured the MTF of their displays, and verified that their CRT had a higher resolution than their LCD. When relating these results to their visual search task, however, they used the MTF only to qualitatively distinguish their displays as of either low or high resolution. Clearly, if they had instead used a visually relevant measure of resolution, the display-type and contrast variables could have been better specified. In fact, it may have even been possible to combine those two variables into a single variable that was directly related to resolution. The spatial resolution technique used in the present study addresses the problems discussed above in that it is objective, and it does not rely on complex calculations that may be implemented and interpreted differently by different experimenters, especially those working in different fields such as display design and visual research. In addition, the results of the technique (i.e. a direct specification of the number of resolved lines) are intuitive and hence more readily applied in the context of visual or perceptual research.

It should be noted that there are also limitations associated with the spatial-resolution technique used in the present study. We have discussed several practical disadvantages in using the MTF for specifying display resolution. However, the MTF and related techniques have many useful features not shared by the present technique. For instance, if several systems were being combined (e.g. a display device and an associated projection system), the MTF approach may provide a means of directly characterizing the resultant projected image. Also, the spatial-resolution technique used here does not fully take into account the effect of pixel-count on the ability to display spatial detail. Pixel-count and display resolution can independently affect image quality, and so both should be considered when evaluating displays. The present techniques can be used to do this, but an additional term would have to be specified [1,16]. Finally, the spatial-resolution technique used here requires that a criterion contrast level be selected in order to estimate the number of resolvable lines. We chose a criterion level of 0.25, which is also suggested by VESA for the evaluation of full grayscale imagery. We are aware of only one attempt [18] to estimate an appropriate response level for visual imagery, and those results support a response level near 0.25. However, that study was limited in scope and preliminary in nature, and so the specification of an appropriate criterion response level remains an open question in the interpretation of spatial-resolution measurements such as those described here.

5.3. Target-size calibration

Target-size is equivalent to target distance and so is a very important variable in flight-simulator applications such as close air support, basic combat maneuvering, and formation flight. For the target-size calibration data of Experiments 1 and 2, nominal target size is always greater than the mean of the measured target-size distributions (see Figs. 3 and 6). This result suggests that a percentile level other than the mean should be used to define actual target size. For the target-size data of Fig. 6 (Experiment 2), the nominal target size is between 20 and 31% larger than the actual target size for all simulated distances. Further, the measured target size distributions do not encompass the nominal size in most cases. For the data of Fig. 3 (Experiment 1), the nominal target size is between 2 and 17% larger than the actual target-size for all simulated distances. Measured target-size distributions for Experiment 1 do encompass the nominal size in most cases. However, the difference between actual target size and nominal target size is not consistent across the various simulated distances. It would be difficult in either case to choose a percentile level that was representative of all simulated distances. In our experience, target-size calibration data are more likely to display the complex relationship between nominal and actual size, which is evident in Fig. 3. Further study will be required to determine whether the data of Fig. 3 or Fig. 6 are more typical, and whether data of that kind can be usefully applied to the calibration of flight-simulator imagery.

5.4. Conclusions

Contrast and resolution are often considered to be independent display characteristics. This is not justified conceptually since a threshold level of contrast must be specified in order to estimate resolution.

The results of Experiments 1 and 2 verify what is typically assumed to be true, i.e. that display-system spatial resolution, as opposed to pixel-count, is the major factor influencing performance on visual tasks requiring high spatial detail. In addition, we have quantified spatial resolution using an objective and intuitive measure, and we have quantified its effect on a perceptual task related to performance in a flight simulator.

Antialiasing levels of 2× and 4× were found to equally improve performance on a target-orientation discrimination task. This result suggests that it may be possible to forego higher levels of antialiasing, and instead use that processing capability for other purposes, such as increasing scene content or system frame rate.

Finally, the differences found between nominal and actual target size indicate that image-size calibrations, which are seldom if ever performed, are required for the accurate simulation of small (i.e. distant) objects.

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An integrated software package for performing the spatial-resolution calibrations described here is included in Ref. [12], and is available either from DTIC or from the authors.

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